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# Evaluation of groundwater resources in the Southern Tihama plain, Saudi Arabia

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**Abstract** In the absence of permanent rivers, groundwater is one of the major water resources in Southern Tihama plain, in the Southwestern Saudi Arabia. Hydrogeological investigation, as well as hydrogeochemical analyses, of 272 groundwater samples was performed to evaluate groundwater resources of shallow alluvial aquifer and their quality for different purposes in the Southern Tihama plain. Hydrogeological investigation revealed that groundwater occurs mainly in alluvium deposits under free water table conditions that range between 9 and 33 m. The calculated hydraulic gradient is inclined towards the west and southwest direction, ranging from 0.001 to 0.005, and soil infiltration rate of coastal plain soils is higher than other soil types. Hydrochemical analysis results indicate that groundwater type is mainly sodium chloride reflecting high amount of minerals. Groundwater in Tihama plain is not suitable for direct drinking and domestic purposes; therefore, it needs a proper treatment to remove high salinity and chloride concentrations. Result also shows that most of the groundwater has high salinity and low sodium hazard, suggesting little danger of exchangeable sodium. Other quality indices such as salinity, chloride, sulfate, and alkalinity range from suitable to high restricting water suitability for some industrial purposes without special treatment or mixing with low saline water.

**Keywords** Tihama plain · Groundwater · Hydrochemical analysis · Hydraulic gradient · Infiltration rate · Drinking · Saudi Arabia

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## Introduction

The Kingdom of Saudi Arabia is classified as a water scarce country, where about 90 % of the total amount of water is lost by evaporation annually. The primary sources of water in Saudi Arabia are groundwater of continental basins that receive water from annual rainfall. The relative uses of groundwater vary significantly between different countries (Perttu 2008; Khaled and Abdalla 2013). Groundwater provides about 50 % of the potable water supplies, 30 % of the industrial water, and 20 % of the irrigation water worldwide. In Saudi Arabia, groundwater contributes to nearly 79 % of the total water supply. It is considered as the main source of irrigation water where about 90 % is consumed in agricultural activity (Al-Turki et al. 2011). In the study area, groundwater is the most important resource used for drinking by many people especially in rural areas. Assessments of groundwater resources are of utmost importance in the arid region, such as Saudi Arabia, where groundwater has critical economical and social significance. The southwestern region of Saudi Arabia is characterized by suitable soils for agricultural investments and sustainable development. In the last few decades, rapid economic growth, intensive agricultural activities, and urban development in the Southern Tihama plain have resulted in decline of groundwater levels, a reduction of well productivity, and quality deterioration.



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The hydrogeology study aims to define aquifer formation, soil infiltration characteristics, and groundwater flow directions in the shallow alluvial aquifer. The hydrochemical investigation aims to evaluate groundwater usability for domestic, irrigation, and industrial purposes.

## Study area

The study area is located in southwestern part of the Kingdom of Saudi Arabia, in an arid zone characterized by humid and hot weather conditions, known as Tihama coastal plain. It extends 30 km between latitude 16° 24′ 26″ and 17° 48′ 29.9″ N and 170 km between longitude 42° 15′ and 43° 00′ E (Fig. 1). The average temperature of the region ranges from 21 °C in winter to 40 °C in summer, and humidity ranges between 89.1 % in winter and 69.4 % in summer. The Tihama coastal plain is separated from Hijaz-Asir highlands by an imposing scarp wall that runs parallel to the Red Sea along 700 km. The Hijaz-Asir highlands rise up abruptly 1.500–3.000 m to the east of the Tihama coastal plain and dip gently towards Najd in the east.

## Geological and hydrogeological setting

The Southern Tihama plain is underlain by tightly folded, regionally metamorphosed volcaniclastic and epiclastic rocks and many mafic to felsic plutonic of late Proterozoic Arabian Shield. Paleozoic sandstones, comprising the Cambrian-Ordovician Wajid sandstone, are found on the southeastern range of the study area and overlie Proterozoic rocks. Several episodes of volcanism are recognized in the geologic time, where younger Tertiary and Quaternary basalt flows and gabbroic dikes are found in the north of the study area (Fig. 2). Quaternary sediments which consist of alternating layers of sand, gravel, and clayey sand are driven from the host rocks and are considered the main shallow aquifer in the study area. They formed during an active period of erosion, following the uplift of the region and opening of the Red Sea. Development of wadi system draining from east to west is bound the Red Sea escarpment.

Structural setting of the area was subjected to many tectonic activities between the Cambrian and Quaternary. The prominent structural features in the area are faulting and jointing (Basahel et al. 1983). Bedrock topography is markedly

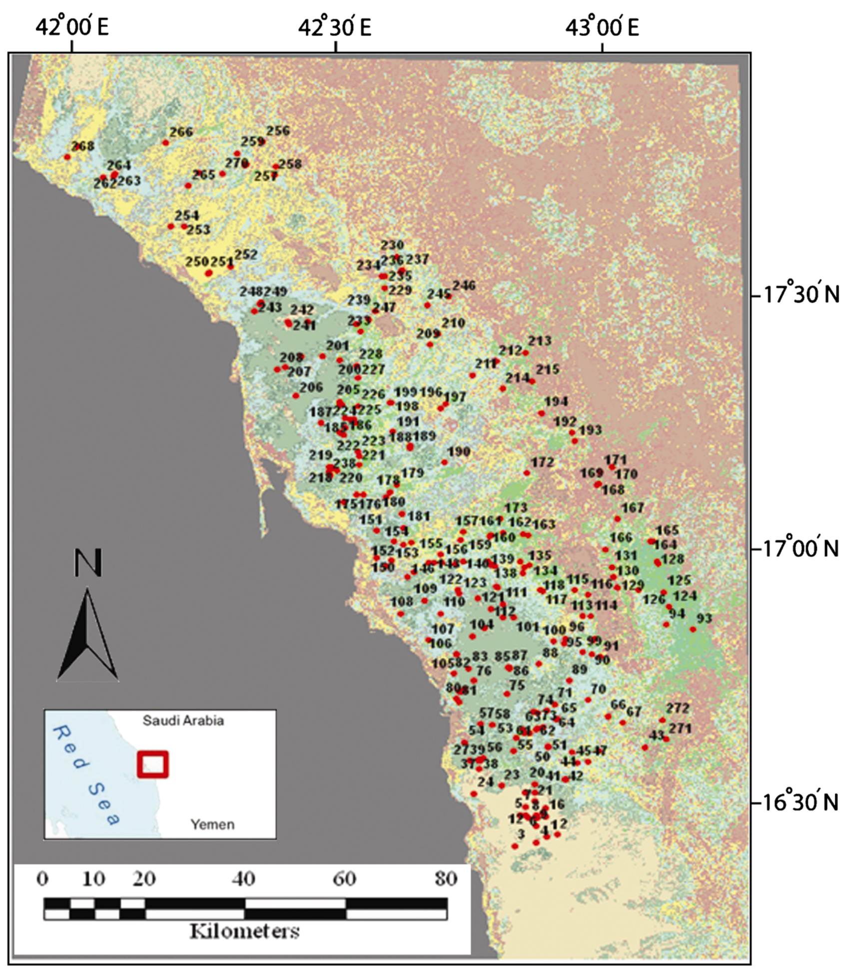
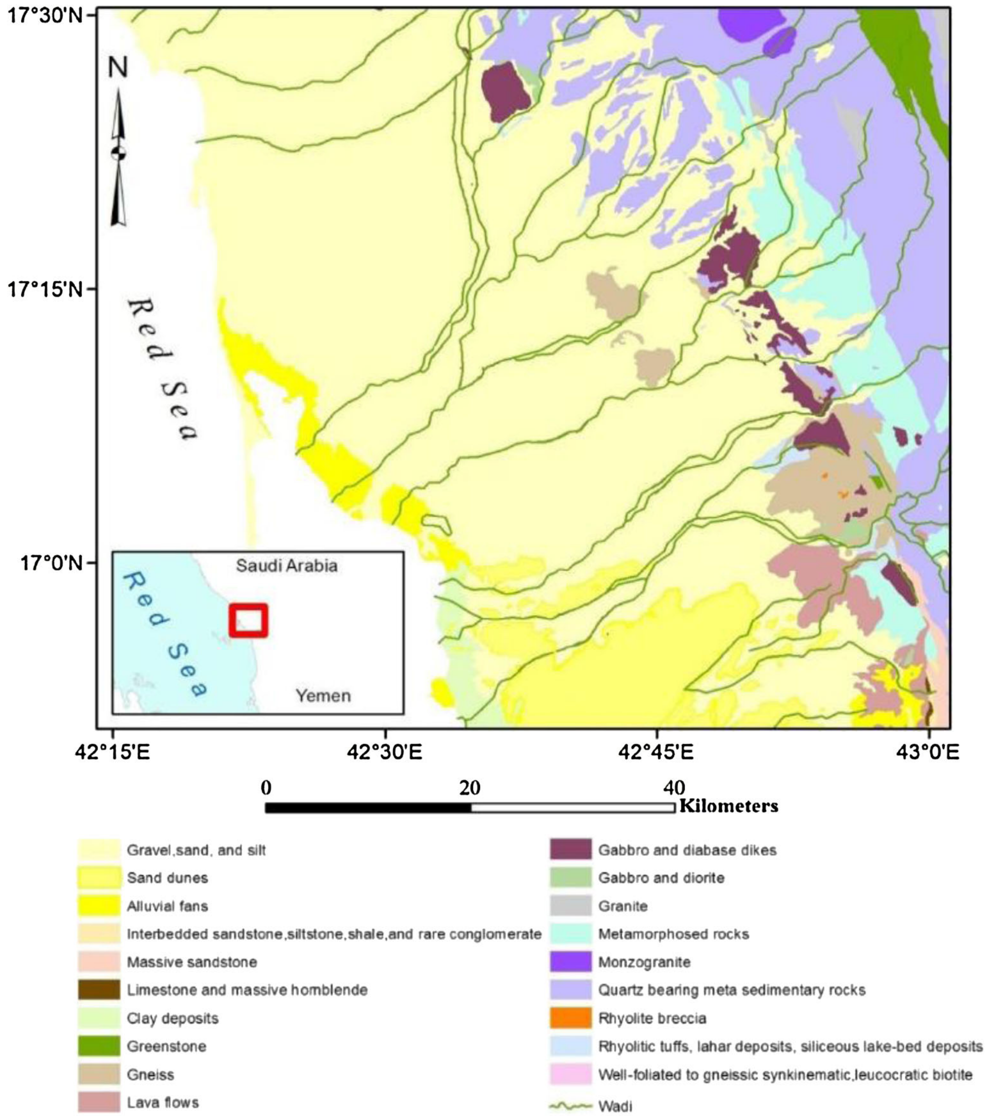



**Fig. 1** Location map of the study area showing groundwater sampling points

**Fig. 2** Geologic map of the study area (Mogren et al. 2011)




affected by normal faulting which tends to form graben and horst structures trending N–S parallel to both the Red Sea axis and foothill exposure (Smith and Al-Mooji 1985). Shallow alluvial aquifers beneath the wadi systems and deep aquifers of fractured Precambrian basement rocks in the mountainous parts are found in the area (Basahel et al. 1983; Hussein and Ibrahim 1997; Hussein and Bazuhair 1992; Al-Shaibani 2008; Al-Bassam and Hussein 2008). In Southern Tihama plain, the alluvial aquifer is the primary source of water for agriculture, domestic, and industrial uses, where groundwater occurs in wadi alluvial deposits and Cretaceous–Tertiary sedimentary rocks (Batayneh et al. 2012). Tertiary and Quaternary basalt aquifers occur in the north of the study area between Makkah and Madinah region. They constitute good aquifers because of both primary porosity (porous zones of basalt flows) and secondary porosity (faults and fractures). Tertiary and Quaternary alluvial aquifer is located in extensive areas, along the Red Sea coastal strip, along wadi courses, mountainous basins, and eolian sands (Fig. 3).

The thickness of the alluvium sediments in the study area varies from 10 m near the foothills to more than 100 m in the southwestern parts away from the highlands. A typical main wadi channel is characterized by a width that ranges from about 100 to 1,000 m. The average thickness of the water-bearing unit varies from about 3 m in the upstream part to about 40 m or more in the downstream (Hussein and Ibrahim 1997; Al-Amri 1998; Al-Bassam and Hussein 2008; Mogren et al. 2011; Batayneh et al. 2012). A significant increase in aquifer thickness was due to structural control, which occurs about 20 km from the coast (Smith and Al-Mooji 1985). Transmissivity value varies between 144 and 5,760 $m^2$/day and specific yield ranges between 0.001 and 0.006 (Al-Ahmadi and El-Fiky 2009) increasing towards west directions. These values indicate that the aquifer in this location

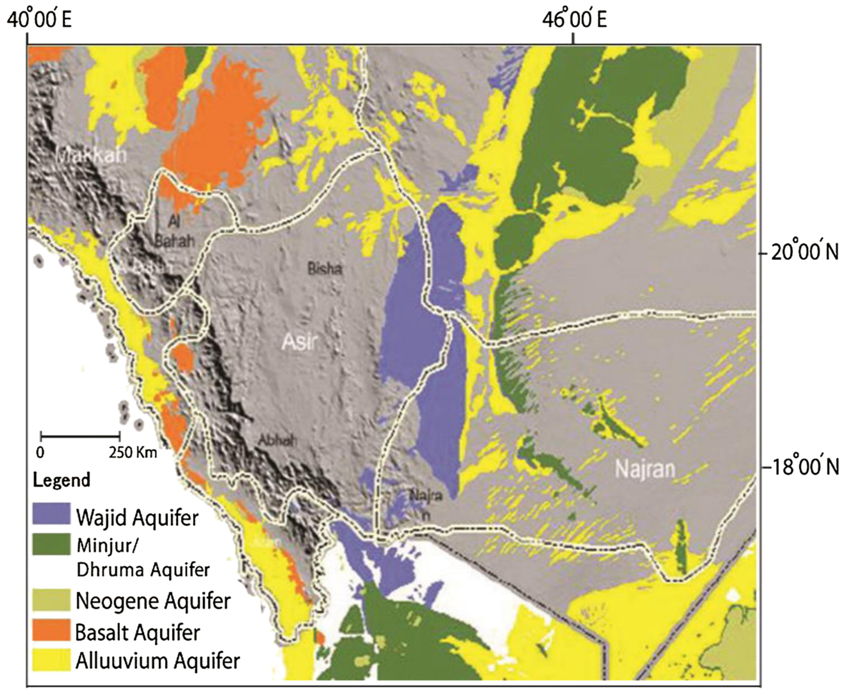



**Fig. 3** Main aquifers cropping out in the study area modified after Japan International Cooperation Agency (2010)

is very good in both productivity and accessibility of water to the well.

The main recharge of the alluvial aquifer is local rainfall infiltration where the southwestern region is rich in rainfall compared to other regions of the Kingdom of Saudi Arabia. Groundwater recharge exclusively occurs during floods in the winter season. An effective use of recharging facilities such as recharge dams and trenches to promote water infiltration into the aquifer is necessary to improve recharge efficiency and to save water from discharging into the Red Sea. The soil infiltration rates obtained from the field infiltration tests revealed that their values in coastal plain soils are higher than these in pediplain and lava field volcanic hill soils. This is because of the coastal plain soils that are mostly sandy textures while the pediplain and lava field volcanic hill soils are mostly fine textures with a high proportion of pebbles and stones that impede the movement of water in the soil. Discharge from the aquifer takes place through artificially withdrawn uncontrolled pumping for different purposes. The natural discharge of groundwater is by evapotranspirational losses in places where the water table is close to the ground surface and base flow.

## Methodology

Detailed hydrogeological investigation was conducted to investigate the hydrogeological conditions in the study area including water level measurements. The fieldwork was carried out in the framework of the land resource assessment and water quality evaluation in Southern Tihama plain. The work included a collection of 272 groundwater samples from wells tapping the alluvial aquifer. Ten water infiltration tests under field conditions using disk infiltrometer were carried out in different soil types to determine the infiltration rate through the soil layer into the aquifer. Computer program "Rosetta" v1.2 (Schaap 2000) was used to calculate the best fit of the infiltration curve. This was done by automatically fitting experimental infiltration test data to the van Genuchten equation (van Genuchten 1980) in a least square method with the help of mechanical analysis data (ratio of sand, silt, and clay) in the soil sample.

Protocol for sample collection and preservation is essentially as given by the standard methods of APHA (2005). Most of these wells are used for drinking, domestic, as well as agricultural purposes. Geographical coordinates and elevation of each sampling location were recorded using GPS (Fig. 1). Laboratory work included chemical analysis of the collected groundwater samples for pH, electrical conductivity (EC), major cations ($Ca^{2+}$, $Mg^{2+}$, $Na^{+}$, $K^{+}$), and major anions ($HCO_3^{-}$, $SO_4^{2-}$, $Cl^{-}$, $CO_3^{2-}$, $NO_3^{-}$). It was followed by data analyses using, e.g., Surfer 8 (Golden Software, Inc., 2002), ERDAS Imaging 8.7, and ArcView 9.2. The following parameters were calculated to evaluate the suitability of the groundwater quality for domestic purposes (Table 1):

Total dissolved solids (TDS) for the analyzed samples were calculated in milligrams per liter according to this equation:

$$\mathrm{TDS} = \mathrm{SUM}\left(Ca^{2+} + Mg^{2+} + Na^{+} + K^{+} + Cl^{-} + SO_4^{2-}4 + HCO_3^{-}3 + CO_3^{2-}3\right) \quad (1)$$

**Table 1** Statistical details of chemical parameters for the analyzed samples ($n$=272) and water quality parameters for domestic uses according to the Saudi Arabian Standards Organization (SASO 1984)

| SASO | CV (%) | STDEV | Average | Max | Min | Parameter |
|---|---|---|---|---|---|---|
| 6.5–8.5 | 3.93 | 0.30 | 7.64 | 8.68 | 6.33 | pH |
| 1,500 | 90.17 | 1,561.7 | 1,731.5 | 10,022.2 | 36.0 | TDS (mg/l) |
| 0.16–1.60 | 76.70 | 2.14 | 2.79 | 13.73 | 0.20 | EC (dS/m) |
| 500 | 108.00 | 293 | 270.00 | 2,817.00 | 60.00 | TH (mg/l) |
| – | 46.26 | 103.70 | 224.21 | 605.13 | 9.15 | Alkalinity (mg/l) |
| 9.98 | 83.66 | 6.91 | 8.26 | 52.89 | 0.28 | $Ca^{2+}$ (meq/l) |
| 12.49 | 109.74 | 5.63 | 5.13 | 54.30 | 0.11 | $Mg^{2+}$ (meq/l) |
| 8.69 | 89.20 | 12.48 | 13.99 | 69.54 | 0.07 | $Na^{+}$ (meq/l) |
| – | 204.17 | 0. 49 | 0.24 | 4.33 | 0.01 | $K^{2}$ (meq/l) |
| 8.33 | 86.97 | 6.94 | 7.98 | 45.71 | 0.15 | $SO_4^{2-}$ (meq/l) |
| 7.04 | 107.76 | 17.21 | 15.97 | 105.49 | 0.30 | $Cl^{-}$ (meq/l) |
| – | 40.11 | 1.44 | 3.59 | 8.50 | 0.15 | $HCO_3^{-}$ meq/l) |
| – | 300.00 | 0.27 | 0.09 | 1.47 | 0.00 | $CO_3^{2-}$ (meq/l) |
| 50 | 298.19 | 14.79 | 4.96 | 113.23 | 0.00 | $NO_3^{-}$ (mg/l) |
| – | 89.04 | 4.04 | 5.66 | 53.35 | 0.07 | SAR |

*STDEV* standard deviation, *CV* coefficient of variation, *TDS* total dissolved solids, *EC* electrical conductivity, *TH* total hardness, *SAR* sodium adsorption ratio

Total hardness (TH) was calculated as $CaCO_3$ in milligrams per liter by the following equation (Todd 1980):

$$\mathrm{TH} = 2.497\mathrm{Ca}^{2+} + 4.115\mathrm{Mg}^{2+} \tag{2}$$

Soil cumulative infiltration rate $I$ (cm) was calculated according to Zhang (1997) as follows:

$$I = C_1 T1 + C_2 \sqrt{T}2 \tag{3}$$

Where

$C_1$ is an empirical constant factor related to soil hydraulic conductivity, in centimeters per second

$C_2$ is an imperial constant factor related to soil sorptivity, in centimeters per second$^{0.5}$.

$T$ is time in seconds

Sodium adsorption ratio (SAR) in milliequivalents per liter was calculated according to the US Salinity Laboratory Staff (USSL 1954) as follows:

$$\mathrm{SAR} = \frac{\mathrm{Na}}{\sqrt{\frac{1}{2}(\mathrm{Ca} + \mathrm{Mg})}} \tag{4}$$

## Results

Based on the collected climatological data from Sabya, Malaki, and Jyzan meteorological stations, records cover a period of 25 years (1980–2004); the mean annual rainfall distribution in the study area is presented in Fig. 4. Rainfall generally occurs from May to September. The spatial variation of precipitation strongly reflects the effect of topography, where the annual rainfall generally increases in the eastern parts, which receives a considerably higher amount of rainfall (>500 mm/year) as compared to the western part of the study area (<200 mm/year) near the Red Sea coast.

Field infiltration tests (Fig. 5a) were used to determine the quantity of precipitation that will enter the soil for recharging the shallow groundwater aquifer. The cumulative infiltration rate versus time (Fig. 5b) is calculated according to Zhang (1997) under field condition. The minimum cumulative infiltration rate value of $I_{30}$ was with cultivated pediplain of shallow soils (10.30 cm) and the maximum value with non-cultivated coastal plain soils (157.33 cm) with an average of 49.4 cm. Soil permeability coefficient $K$ ranges between 0.61 cm/h (cultivated pediplain with shallow soils) and 20.35 cm/h (non-cultivated coastal plain soils) with an average of 6.29 cm/h, while soil sorpitivity coefficient $S$ ranges between 0.0205 m/s$^{0.5}$ (cultivated pediplain with shallow soils) and 0.36 m/s$^{0.5}$ (cultivated lava field volcanic hill soils) with an average of 0.972 m/s$^{0.5}$. The minimum cumulative infiltration rate value of $I_{30}$ was with cultivated pediplain of shallow soils (10.30 cm) and the maximum value with non-cultivated coastal plain soils (157.33 cm) with an average of 49.4 cm. Soil permeability coefficient $K$ ranges between 0.61 cm/h (cultivated pediplain with shallow soils) and 20.35 cm/h (non-cultivated coastal plain soils) with an average of 6.29 cm/h, while soil sorpitivity coefficient $S$ ranges between 0.0205 m/s$^{0.5}$ (cultivated pediplain with shallow soils) and 0.36 m/s$^{0.5}$ (cultivated lava field volcanic hill soils) with an average of 0.972 m/s$^{0.5}$. The results showed clear variability of soil infiltration properties according to landforms due to soil texture where there were large grain size in the upstream part of the wadi and fine grain size in the downstream part of the wadi.

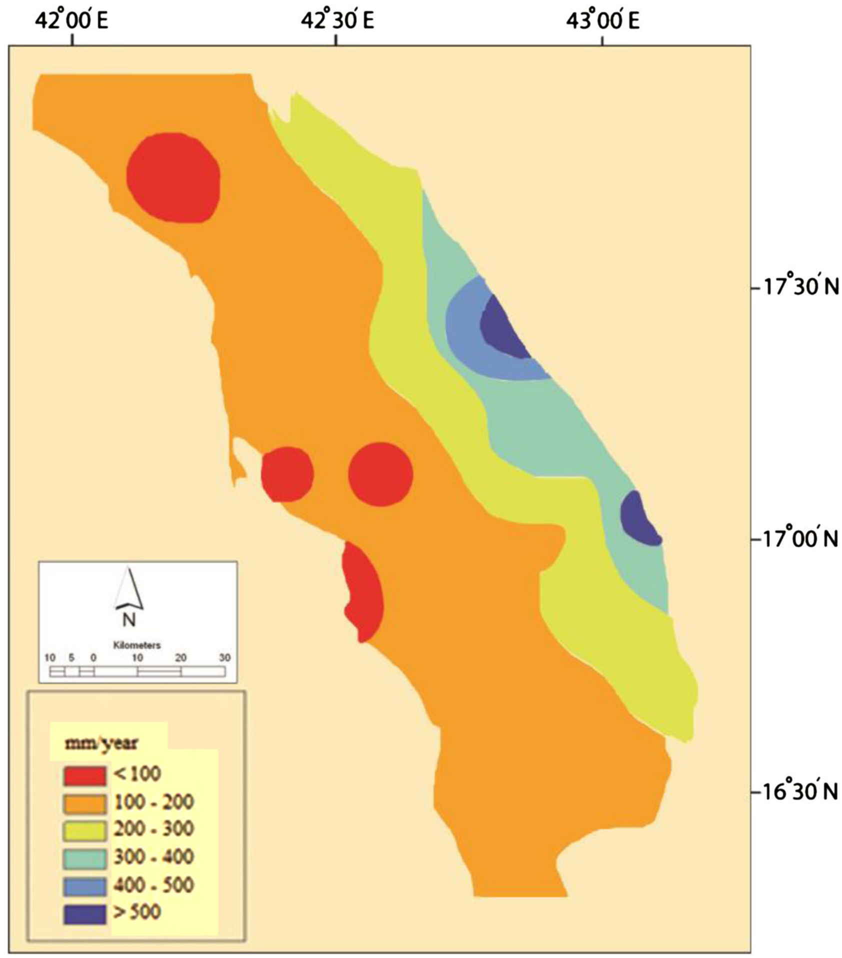



**Fig. 4** Rainfall distribution in the study area

The water elevation contour map (Fig. 6) revealed that groundwater flows towards the west and southwest direction of the region; thus, there is a marked decrease in hydraulic gradients toward the coastal areas. Natural groundwater discharge at the coast has decreased with the falling hydraulic gradients resulting from well abstraction. The total depth of the wells ranges from 19 m (Al-Lgyah well) to 97 m (Al-Gwydyah well), and the well yield ranges between 69 and 154 $m^3$/h.

The calculated hydraulic gradient was about 0.005 in the upper part of the coastal plain and about 0.001 in the coastal strip. The groundwater level varies from 10 m (Al-Abadlah

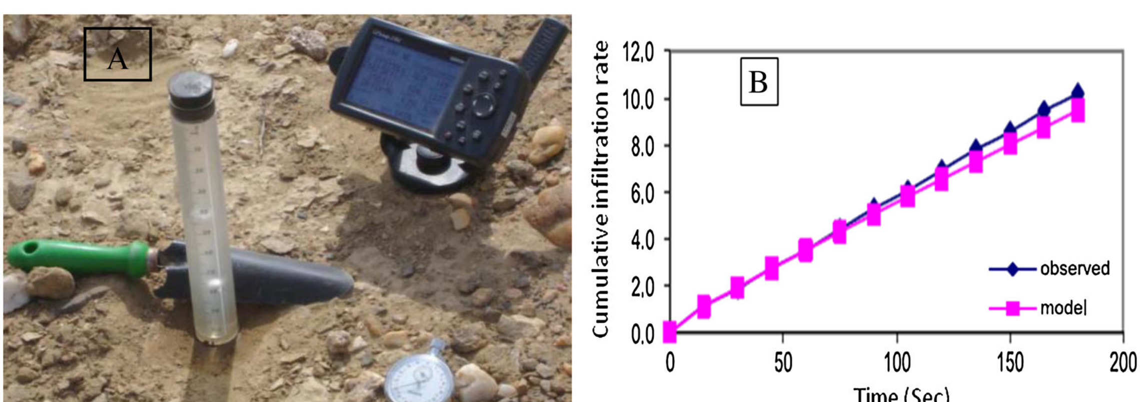



**Fig. 5** Field infiltration test. **a** Field photograph showing the disk infiltrometer. **b** Example of cumulative infiltration rate for non-cultivated coastal plain soils

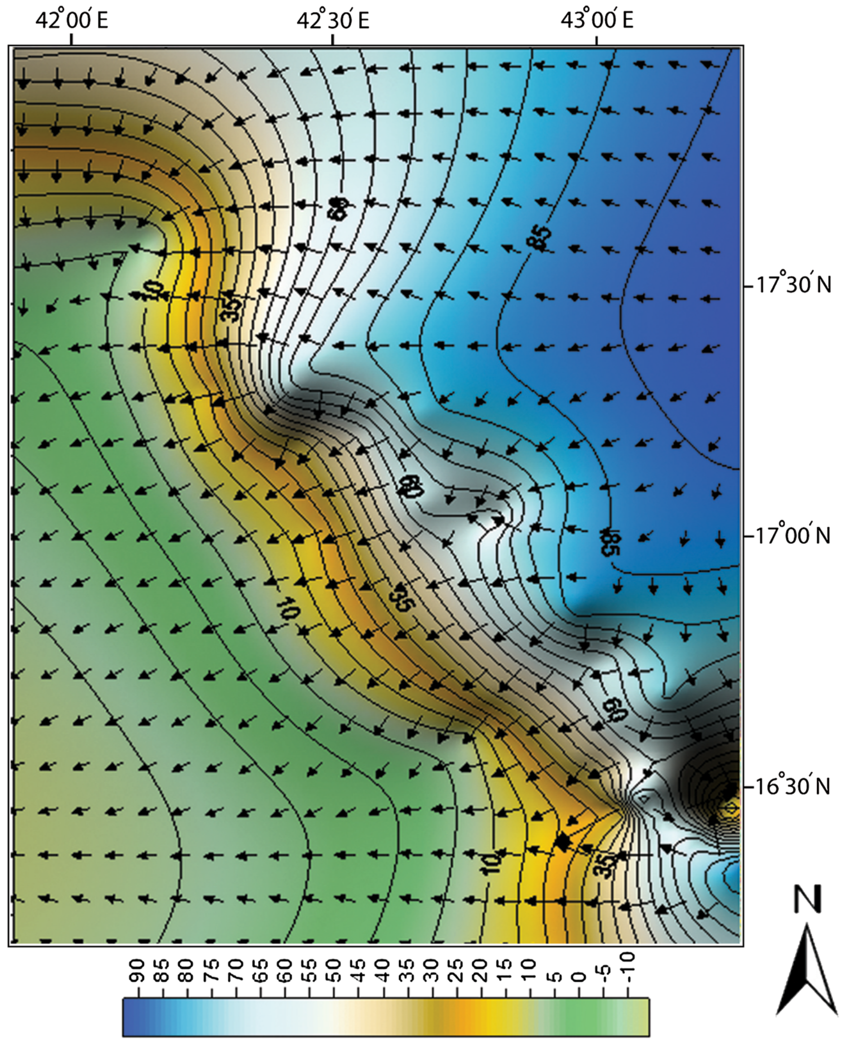



**Fig. 6** Water table contour map of the study area showing the flow directions

well) to 33.5 m (Al-Gwydyah well) above mean sea level, and in general, the groundwater level rises eastward towards the highlands.

These variations in the water table might be attributed to the variations of bedrock surface in the study area. A comparison of the water levels measured in 1993 with the present situation shows that the water level during the last 20 years has risen in the eastern parts in the coastal plain and fell in the western part of the area.

It may be inferred from the data presented in Table 1 that there is a wide range of salinities and chemical compositions as shown from the values of standard deviation with respect to the EC, $Na^{+}$, $Mg^{2+}$, $Ca^{2+}$, $Cl^{-}$, and $SO_4^{2-}$ contents. Such wide ranges of chemical compositions suggest that multiple sources and/or complex hydrochemical processes regulate the chemical composition. Generally, groundwater chemistry mostly arises from the source and circulation of the water itself into the aquifer media, where geology imposes its chemistry on the groundwater composition.

The pH value ranges between 6.33 and 8.68 with an average of 7.64 mg/l indicating mildly acidic to alkaline nature of the water. The EC is a useful tool to evaluate the purity of water, and its value is related to total dissolved solids. In the study area, EC value ranges between 0.20 and 13.73 dS/m with an average of 2.79 dS/m indicating moderate and highly saline water.

The EC values increased significantly, perhaps due to the impact of seawater incursion (Fig. 7). Other sources which might have contributed to this high salinity values, including the flushing of the accumulated soluble salts in the top soil to the aquifer (the measured soil salinity at Al-Lkbasay ranges between 0.5 and 21 dS/m) and/or agricultural return flows into the alluvial aquifer. In the study area, salinity increases towards south direction which may indicate the possibility of a high rate of intrusion of saline water due to overexploitation of the wells. Overexploitation by excessive and unregulated pumping (most of the wells are concentrated in southern parts of the study area) has resulted in a high withdrawal of

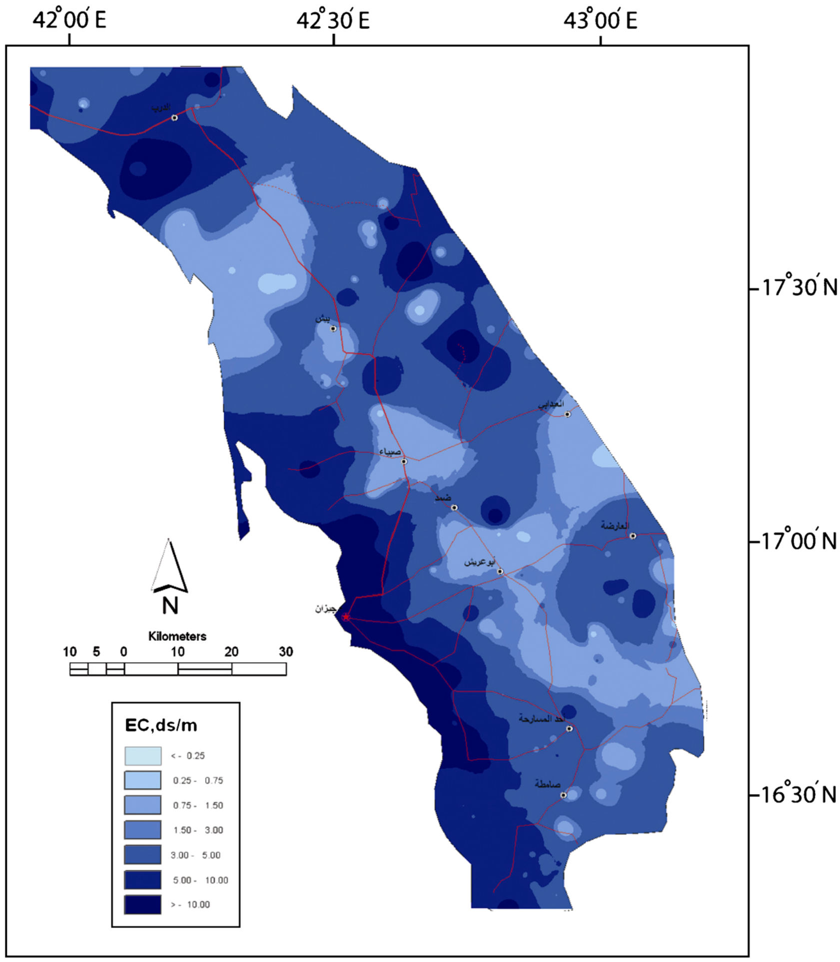



**Fig. 7** EC distributions map the study area

groundwater in such a way that it crossed the sustainable limits. This causes a decline of groundwater levels; thus, seawater intrudes into the aquifer and contaminates groundwater.

TDS measurements denote the various types of minerals present in water in the dissolved form. In natural water, dissolved solids include mainly carbonates, bicarbonates, chloride, sulfate, phosphate, silica, calcium, magnesium, sodium, and potassium. The high positive correlation supports the fact that $Na^+$, $Ca^{2+}$, $Cl^-$, $SO_4^{2-}$, and $HCO_3^-$ constituted the bulk of the ion concentrations. TDS values reflect the level of minerals that are present in water in dissolved form, and it varies considerably in different geological formations owing to differences in the solubility of minerals. In the analyzed groundwater samples, TDS values range between 36.0 and 10,022 mg/l with an average of 1,731.5 mg/l reflecting brackish to saline groundwater character. Water hardness is caused primarily by the presence of cations such as calcium and magnesium for TH and anions such as carbonate and bicarbonate for carbonate or temporary hardness (CH). In the study area, TH varies between 1.2 to 355 mg/l; high values of total hardness may be due to marine salt contamination and the occurrence of some gypsum deposits in sabkha.

Chemical analysis of water samples indicated that the most dominant cation chemistry shows the dominance of $Na^+$ (50.23 %) followed by $Ca^{2+}$ (29.46 %) and $Mg^{2+}$ (18.33 %), while the anion is $Cl^-$ (57.19 %) followed by $SO_4^{2-}$ (28.56 %) and $HCO_3^-$ (12.84 %), with minor contribution from $CO_3^{2-}$ and $NO_3^-$. Thus, groundwater type is sodium chloride reflecting high amount of minerals. Sodium concentrations, the dominant cation, range between 0.07 and 69.54 meq/l with an average of 13.99 meq/l, where $K^+$ ion concentrations vary from 0.01 to 4.33 meq/l. The elevated level of $Na^+$ might be due to the long residence time of water, dissolution of minerals from lithological composition (weathering of feldspar), possible ion exchange processes which withdraws $Ca^{2+}$ and gives $Na^+$ to the solution, and also due to overexploitation of groundwater as well as the addition from the irrigation waters. The low levels of $K^+$ in natural waters are a consequence of its tendency to be fixed by clay minerals and to participate in the formation of secondary minerals (Mathess 1982). The $Ca^{2+}$ and $Mg^{2+}$ concentrations vary from 0.28 to 52.89 and 0.11 to

54.3 meq/l with averages of 8.26 and 5.13 meq/l, respectively. These cations are possibly derived from chemical weathering of the silicate rocks (feldspars, micas, and other related minerals constituting the basement rocks) in the area.

Generally, greater mineralization of groundwater within the study area is associated with higher chloride and sulfate concentrations. The chloride ion occurs in natural waters in fairly low concentrations, usually less than 100 mg/l, unless the water is brackish or saline (Fetter 1999). In the study area, the impact of seawater incursion perhaps plays an important role in the high chloride concentrations. In addition to mixing with seawater, industrial, domestic sewage, and leaching from upper soil layers in such dry climates might be contributed to the high level of chloride in groundwater (Srinivasamoorthy et al. 2008). Chloride concentrations, the dominant anion, range between 0.30 and 105.49 meq/l with an average of 15.97 meq/l, where sulfate concentrations vary from 0.15 to 45.71 meq/l with an average of 7.98 meq/l. Bicarbonate anion ranges between 0.15 and 8.5 meq/l with an average concentration of 3.6 meq/1; the source of bicarbonate may be attributed to the charged/recharged $CO_2^{2-}$. Bicarbonate has been found in abundance in groundwater, but it occurs in small quantities in seawater. So, these two parameters, chloride and bicarbonate, may highly indicate the salt water intrusion into groundwater aquifers. Agricultural activities on top, especially inorganic fertilizer or contamination from human or animal wastes as a consequence of the oxidation of ammonia, are the predominant sources of nitrate in groundwater. The minimum, maximum, and average nitrate concentrations in the area are 0, 113.23, and 5 mg/l, respectively.

Seawater intrusion is highly associated with groundwater withdrawal. Ionic ratios (rNa/rCl and rCl/r$HCO_3$ + $CO_3$) were calculated in milliequivalents per liter to evaluate the extent of seawater effect on the freshwater aquifer in the study area (El Moujabber et al. 2006; Lee and Song 2007; Abdalla and Khalifa 2013). rNa/rCl ratios less than the seawater ratio (0.86) indicate that fresh groundwater was contaminated with the saline water. The calculated rNa/rCl ratios showed that 106 samples (39 %) are less than the seawater ratio indicating contamination by seawater to some extent, while 27 samples (9.9 %) are close to the seawater value indicating recent simple mixing with seawater (Mercado 1985). These wells are mostly located in the southern and western parts in the study area, in particular, close to the Red Sea coast. The rest of the samples exceeded the seawater value, which might be due to anthropogenic sources that reflect meteoric water recharges. The hydrochemical data showed that the collected groundwater samples have rCl/r$HCO_3$ + $CO_3$ ratio ranges between 0.35 and 64.65. The effect of seawater encroachment could be classified using rCl/r$HCO_3$ + $CO_3$ ratio based on Revelle (1941) and Todd (1959). Ratio values showed that 256 samples (94.1 %) have rCl/r$HCO_3$ + $CO_3$ >0.5 indicating simple mixing with seawater, while the rest of the samples are unaffected by seawater intrusion. Out of the 256 samples, 182 samples (71 %) have rCl/r$HCO_3$ + $CO_3$ ratio ranges between 0.5 and 6.6 that indicated slightly and moderately affected by seawater intrusion, while the other 74 samples (29 %) have rCl/r$HCO_3$ + $CO_3$ >6.6 which indicates that it is strongly affected by seawater intrusion. These affected samples are found to be located near the coast, may be due to seawater intrusion. Periodic chemical analysis of groundwater along with reducing the exploitation activities helps track the seawater intrusion especially in coastal parts. Still, the problem needs further studies to be more accurately quantified and to assess the seawater encroachment for the groundwater aquifer in the study area.

## Discussion

In the study area, groundwater is being mostly used for domestic purposes especially for people in rural parts. Water for domestic uses must be odorless, colorless, and free from harmful bacteria, viruses, and radioactive elements. Saudi Arabia relies mainly on groundwater and desalinated water for drinking purposes. Water from these sources must be treated to make it suitable for drinking. Saudi Arabian Standards Organization (SASO) (1984) provides the country's water quality specifications for both bottled and unbottled drinking water (Table 1).

In general, all of the water samples have pH values falling within the limits of the standards prescribed by SASO except one sample has pH value <6.5 and two samples have pH >8.4. EC ranges between moderate and highly saline water and in most samples EC values are above permissible limits prescribed by Standards for Drinking Water, SASO, and WHO. There is no proof of negative health effects associated with the ingestion of high TDS water (WHO 2006). However, some studies suggest that the continuous consumption of saline water may lead to human conditions of hypertension like those found by Khan et al. (2008). Groundwater with a TDS value less than 500 mg/l can be considered as excellent for drinking purpose (WHO 1984). In almost all the water samples, the TDS values vary widely and exceed the recommended limits of the WHO (1984) and SASO (1984), and accordingly they are not suitable for drinking and domestic uses without removing the exceeding TDS or dilution with water of low TDS. Hard water is not a health hazard but it may be unsuitable for domestic use especially with laundry.

Quantitative classification of groundwater according to their level of hardness (Sawyer and McCarty 1967) showed that only 1 % of the examined water samples is soft water (<75 mg/l), 3 % fall under moderately hard (75–150 mg/l), 14 % fall under hard (150–300 mg/l), and the rest are very hard (>300 mg/l). With respect to TH value set by SASO, most of the studied water samples exceeded the recommended maximum permissible level (500 mg/l). Sodium concentration values indicate that 257 samples (94.85 %) are above the permissible limits prescribed by the Standards for Drinking Water, where $K^+$ ion concentrations vary from 0.01 to 4.33 meq/l. Calcium and magnesium concentrations in 195 samples (71.69 %) and 247 samples (94.3 %), respectively, are within the permissible limits prescribed by Standards for Drinking Water ($Ca^{2+}$=200 and $Mg^{2+}$=150 mg/l). Chloride salts in excess of 100 mg/1 give salty taste to water, so it is recommended that chloride content should not exceed 250 mg/1 (SASO 1984). $Cl^-$ concentrations in 86 samples (31.6 %) are within the permissible limits where sulfate concentrations of 166 samples (63.36 %) are within the permissible limits (400 mg/l) prescribed by the SASO. Excess sulfate causes a laxative effect on human system with the excess magnesium in groundwater. $HCO_3^-$ concentration values indicate all samples are within the permissible limits. Serious health implications are associated with increased nitrate concentrations in drinking water. Infants under 6 months of age are susceptible to nitrate poisoning which is called methemoglobinemia or "blue baby syndrome"; thus, the affected baby suffers oxygen deficiency (Craun 1984). In almost all the water samples, nitrate concentrations are below the recommended limits except nine water samples (3.44 %) which exceeded the maximum allowed nitrate levels for drinking water. Water has to be analyzed for trace element and for microbiological content before use for domestic purposes.

Excess salt increases the osmotic pressure of the soil water and produces conditions that keep the roots from absorbing water. This results in physiological drought conditions. Salinity hazard in irrigation water can be expressed in terms of EC, and high salt content in irrigation water leads to the formation of saline soil. Moreover, irrigation by saline groundwater causes recycling of salts and their accumulation in the shallow aquifer where salts are accumulated in the soil and flushed through the unsaturated zone to the aquifer.

According to USSL (1954) classification (Table 2 and Fig. 7), EC values of groundwater indicate that 0.38 % of the samples have low salinity hazard class C1 (<0.25 dS/m) which can be used for irrigation of most crops and the majority of soils. While the 8.02 % of the samples are medium salinity hazard class C2 (0.25–0.75 dS/m), and it can be used if a moderate amount of leaching occurs. About 42.37 % of the samples are high salinity hazard class C3 (0.75–2.25 dS/m) and thus may be considered as suitable for irritation. However, about 49.24 % belong to very high salinity hazard class C4 (>2.25 dS/m) which are unsuitable and require high leaching before usage. High salinity water (class 4) is suitable for irrigating high salt-tolerant crops.

SAR or sodicity index is a significant relationship between SAR values of irrigation water and the extent of sodium absorption by the soil. If the water used for irrigation is high in sodium and low in calcium, the cation exchange complex may become saturated with sodium. This can destroy the soil structure owing to dispersion of clay particles (Malviya1 et al. 2011), and high sodium content SAR in irrigation water leads to development of an alkaline soil. The SAR values varied from 0.07 to 53.35 with an average value of 5.66, where in most of the cases these values are below permissible limits prescribed by USSL (1954).

Regarding the relative tolerance of crop plants to sodium hazard (Table 3), majority of water samples (88.5 %) have low sodium hazard, class S1 (<10), and can be used for most crops, whereas 9.54 % of the samples have medium sodium hazard, class S2 (10–18), and 1.53 % of the samples are high sodium hazard, class 3 (18–26), and only one sample has very high sodium hazard, class S4 (>26), which can be used for tolerant crops only, especially in sandy soils. The analytical data, resulted from EC and SAR (Tables 2 and 3), illustrates that most of the groundwater samples fall in the fields of C4S1 and C3S1 indicating high to very high salinity hazard and low sodium hazard water, which can be used for irrigation on almost all types of soil with little danger of exchangeable sodium.

More information about the suitability of groundwater in the study area for irrigation purposes can be found in Al-Turki et al. (2011). They evaluate the suitability of groundwater for irrigation purposes based on the irrigation quality parameters such as soluble sodium percentage (SSP or %Na), residual sodium carbonate (RSC), effective salinity (ES), and potential salinity (PS) in addition to soil type, crop type, and crop pattern. Their results revealed that the water is good to permissible quality and can be used for irrigation.

The study area is considered as one of the most promising industrial areas in the kingdom. Thus, the evaluation of groundwater quality for industrial purposes is very important. Water with high levels of chloride, sulfates, and sodium or

**Table 2** Quality requirements for irrigation based on EC (USSL 1954)

| EC (dS/m) | Salinity hazard | Water class | Representing sample (%) |
|---|---|---|---|
| ≤0.25 | C1 | Excellent | 0.38 |
| 0.25–0.75 | C2 | Good | 8.02 |
| 0.75–2.25 | C3 | Doubtful | 42.37 |
| >2.25 | C4 | Unsuitable | 49.24 |

*EC* electrical conductivity

**Table 3** Quality requirements for irrigation based on SAR (USSL 1954)

| SAR | Sodicity hazard | Water class | Representing sample (%) |
|---|---|---|---|
| <10 | S1 | Excellent | 88.5 |
| 10–18 | S2 | Good | 9.54 |
| 18–26 | S3 | Doubtful | 1.53 |
| >26 | S4 | Unsuitable | 0.33 |

**Table 4** Water quality requirements for some industries (National Academy of Science 1972)

| Chemical parameter | Type of industry | | | | Average measured value |
|---|---|---|---|---|---|
| | Food | Petroleum | Paper | Textile | |
| pH | 6.5–8.5 | 6–9 | – | – | 7.64 |
| TDS | 500 | 3,500 | 200–500 | 100–200 | 1,731 |
| $Na^+ + K^+$ | – | 230 | – | – | 331 |
| $Ca^{2+}$ | 100 | – | – | – | 165 |
| $Mg^{2+}$ | – | 85 | – | – | 62 |
| $HCO_3^- + CO_3^{2-}$ | | 480 | | | 224 |
| $SO_4^{-2}$ | 250 | 900 | | 100 | 383 |
| $Cl^-$ | 250 | | 0–200 | 100 | 566 |
| Alkalinity | 250 | 500 | 75–150 | 50–200 | 224.21 |
| Hardness | 250 | 900 | 100–200 | 0–50 | 270 |

All chemical parameters in milligrams per liter except pH

*TDS* total dissolved solids

other ions will increase the water conductivity and may promote corrosion (Wilkes University 2002), where chloride combines with calcium and magnesium, and increase the corrosive activity of water, depending on the alkalinity of the water. This can increase the concentrations of metals in the water supply. With respect to water hardness, water of levels above 300 mg/l is considered excessive for a public water supply and results in a high soap consumption as well as objectionable scale in heating vessels and pipes; most of the tested samples do not comply with the range of TH values set by SASO and National Academy of Science (1972) for all industries except petroleum industries. On the other hand, TDS, chloride, sulfate, and alkalinity values, in most of tested samples in the study area, are not suitable for fruit, vegetable paper, and textile industry (Table 4). This indicates the need for special treatment or mixing with some distilled water prior to use.

## Conclusion

Based on the hydrogeological investigation, groundwater exists under unconfined conditions with water level ranging between 9 and 33 m, influenced by percolation from precipitation. The calculated hydraulic gradient within the aquifer ranges from 0.005 to 0.001 towards the coastal zone. The result of the infiltration tests showed a clear variability of soil infiltration properties which may be attributed to the nature of the soil mechanical composition and soil texture, where the coastal plain soils are mostly sandy textures while the pediplain and lava field volcanic hill soils are mostly fine textures with high proportion of pebbles and stones that impede the movement of water in the soil.

On the other hand, the chemical analysis results as well the assessment of waterquality revealed that the abundance of the major ions is in the following order: $Na^+ > Ca^{2+} > Mg^{2+} > K^+ = Cl^- > SO_4^{2-} > HCO_3^-$ reflecting sodium chloride water type. The ionic ratios ($rNa/rCl$ and $rCl/rHCO_3 + CO_3$) and EC values indicate that the groundwater in the study area has a mixed origin that is possibly infiltration of pure meteoric water affected by seawater intrusion. Further, it was clear that the higher values of TDS and EC observed in the southern and western parts, in particular, close to the Red Sea coast reflecting are a gradual increase from upstream to downstream which coincides with the groundwater flow direction. From a careful examination of these data, it was clear that the $Na^+$, $Mg^{2+}$, $Cl^-$, and $SO_4^{2-}$ ions showed a wide range of distributions and high standard deviations which may suggest a possible incursion of nearby saline water. Chemical weathering and dissolution of minerals within a geologic formation through which water flows also play an important role in the water chemistry. The study revealed that groundwater reflects the brackish to saline water category accordingly. It mostly does not suit domestic uses due to the high salinity and chloride concentrations particularly in the coastal areas; meanwhile, it could be used for industrial purposes with some restrictions. TH values revealed that more than 80 % of the studied water samples are very hard water (>300 mg/l) based on Sawyer and McCarty's (1967) classification. For agricultural purposes, special management of salinity control and certain kinds of plants with good salt tolerance should be considered. According to the criteria of the National Academy of Science (1972), most water in the study area is not suitable for many industrial purposes without special treatment or mixing with low saline water. From a strategic vision and plan for the development and management of water resources in southwestern region of the kingdom, it is necessary to establish a number of multifunctional dams. These dams must be accompanied by a number of studies that have managed to exploit the amount of water that is wasted without the possibility of feeding groundwater aquifers. The best locations of these dams are the upper parts of valleys where the region accounts for Jazan and Tihama plains by more than 60 % of the quantities of floods in the kingdom as the total volume of water floods annually is 1,250 million cubic meters. This could increase the amount of surface water and recharge of the groundwater through recharge dams.

Since the study area is relatively vulnerable to the contamination by seawater intrusion, further detailed studies are recommended to examine closely and regularly the groundwater characteristics especially in the coastal area to avoid more seawater encroachment into the aquifer.

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